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# Micro Sun Sensor

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# Introduction

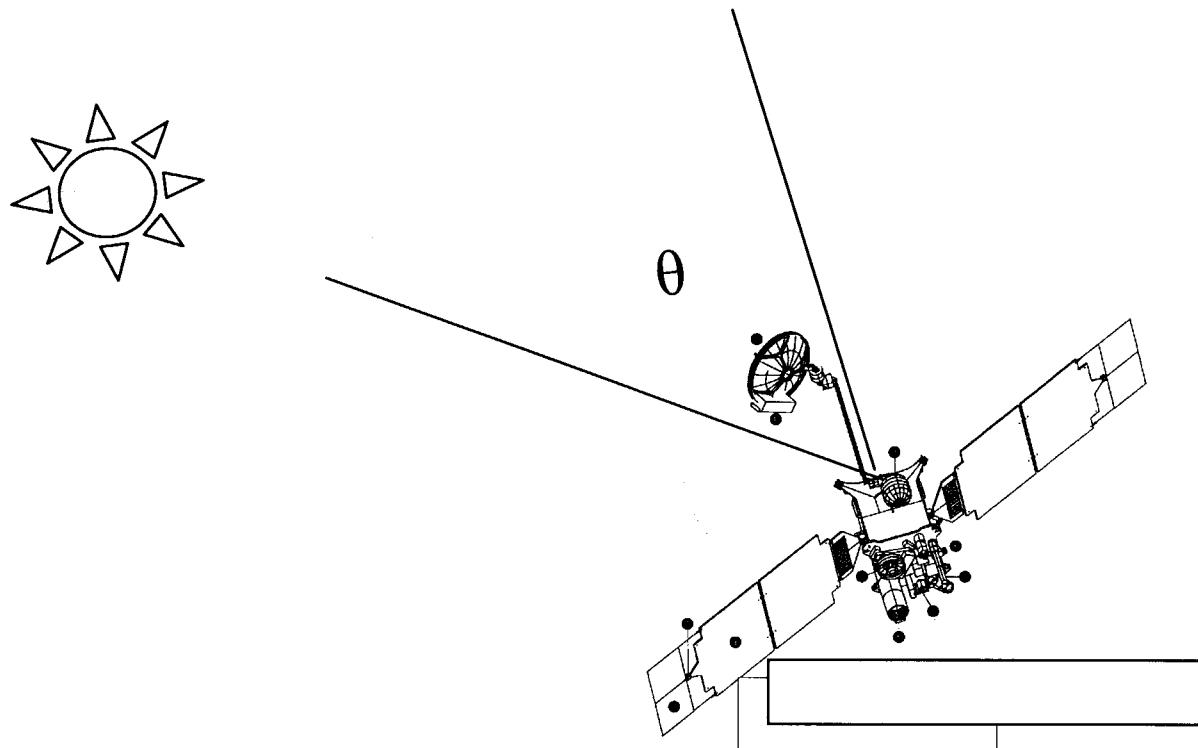
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- **Sun Sensors**
- **Micro Electro-Mechanical Systems (MEMS) Mask**
- **APS Detector**
- **Conventional Image Processing**
- **Fuzzy Image Processing**
- **Tests**
- **Camera Model/Calibration**
- **Conclusion**



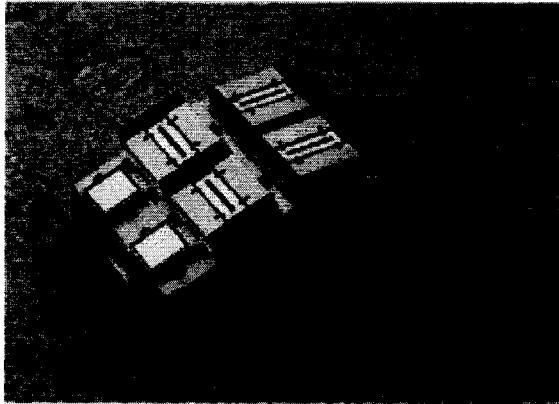
# Sun Sensors

**Sun sensors are used to determine the orientation of the sun relative to spacecraft reference vectors in order to point e.g. solar panel towards the sun or to point an antenna towards earth etc.**



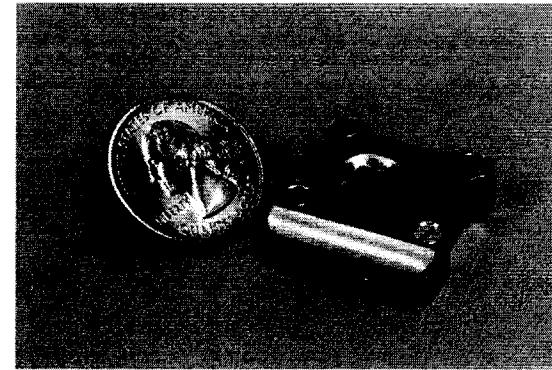


# Sun Sensors



## State of the Art:

Accuracy:  $0.3^\circ$   
Size:  $130 \times 61 \times 48$  mm  
Field-of-view:  $128^\circ$   
Mass: 500 grams  
Power: 300 mW



## Micro Sun Sensor:

Accuracy:  $0.04^\circ$  or better  
Size:  $25 \times 25 \times 8$  mm  
Field-of-view:  $128^\circ$  or larger  
Mass: 11.5 grams  
Power: 20 mW



# Micro Sun Sensor



- **Objective**
  - To develop a low mass (<5 grams) and low power (<20 mW) sun sensor on a 10x15 mm chip with larger than 128° field of view and better than 0.02° accuracy for next generation nanorovers and nanospacecraft
- **Current Status**
  - Developed a small (25x25x8 mm) and low mass (11.5 grams) breadboard using MEMS (mask) and APS (detector) technologies



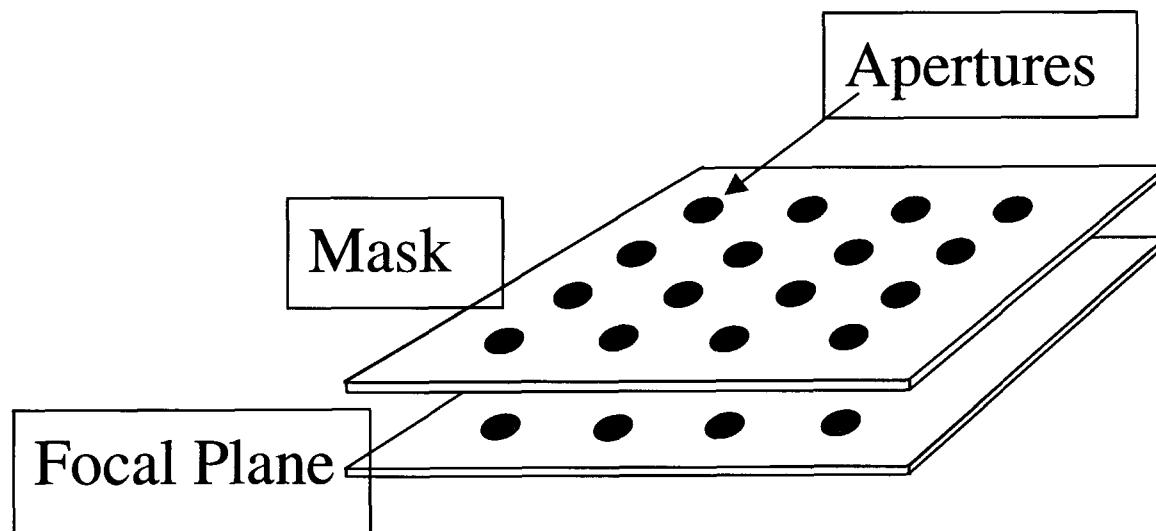
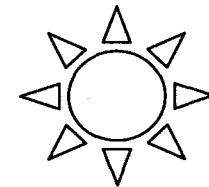
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# Micro Sun Sensors



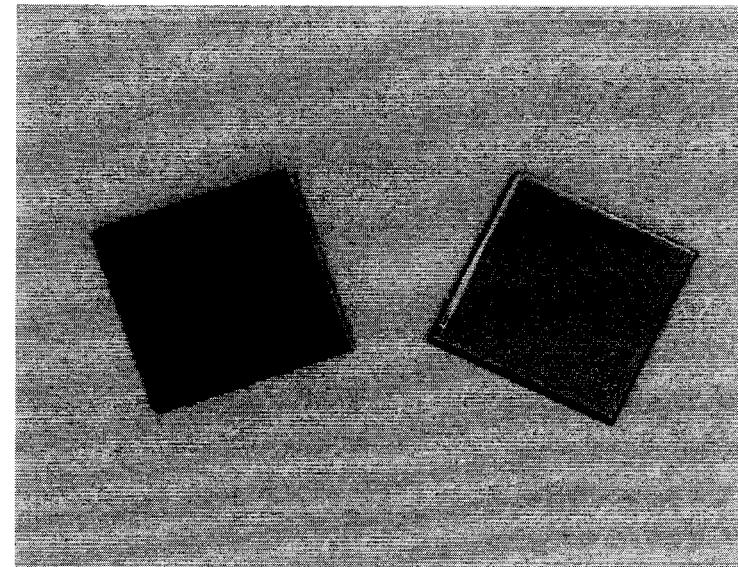
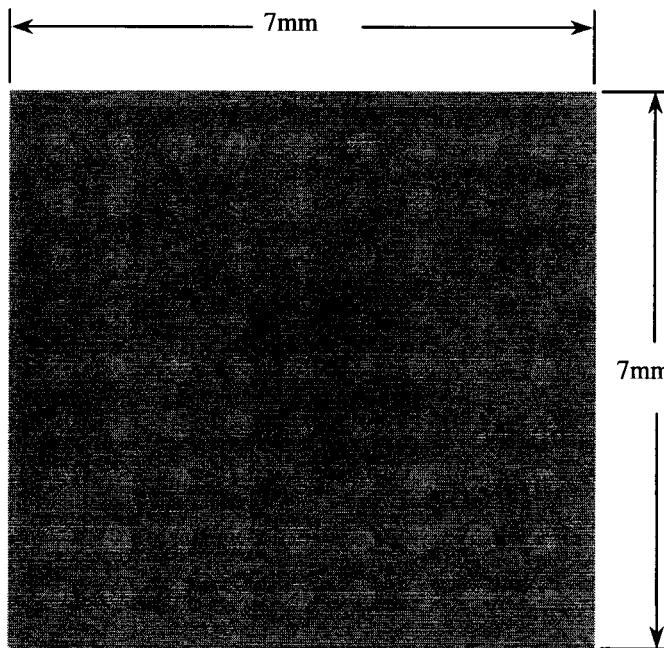
Newly developed sensor operates  
like a sun dial





# MEMS Mask

MEMS mask is made of Silicon wafer with Chrome and Gold layers



= Gold

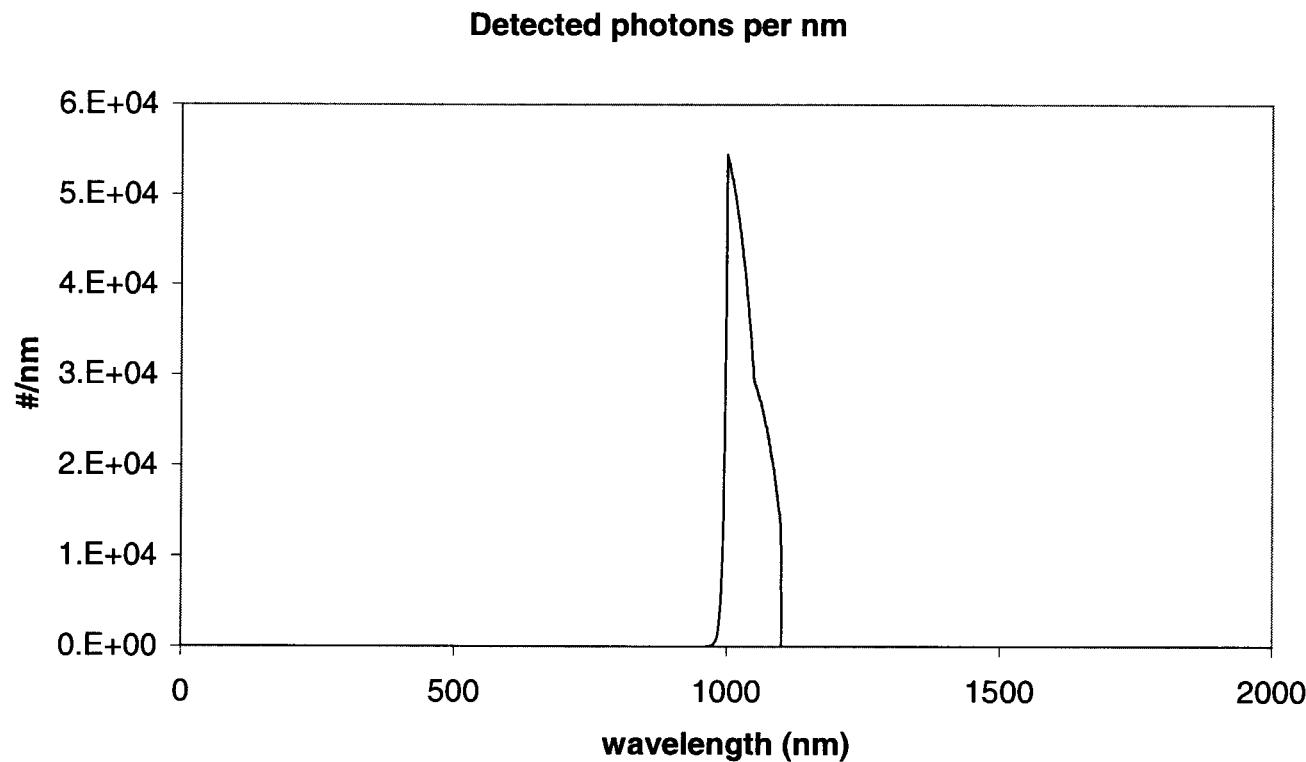


= Chrome



# Spectral Sensitivity of Sensor

- Silicon Wafer thickness: 500 microns
- Chrome thickness: 570 Angstrom
- Reasonable signal levels at 100 milliseconds exposure time



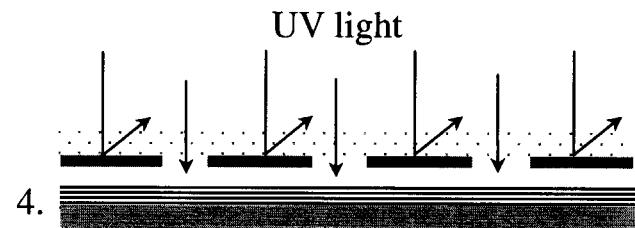


# MEMS Mask Fabrication

1. Start with a  
500 micron thick silicon wafer

2. Deposit 570Å Chrome and 2000Å Gold

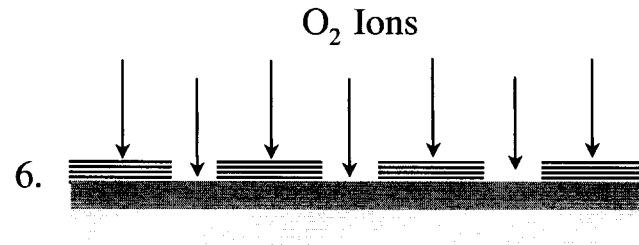
3. Deposit photoresist



4. With UV exposure, the UV exposed photoresist area become etchable and the UV blocked area remains intact in a designated developer



5. Develop away UV exposed photoresist



6. Deposit O<sub>2</sub> Ions in RIE



7. Etch Gold and strip photoresist

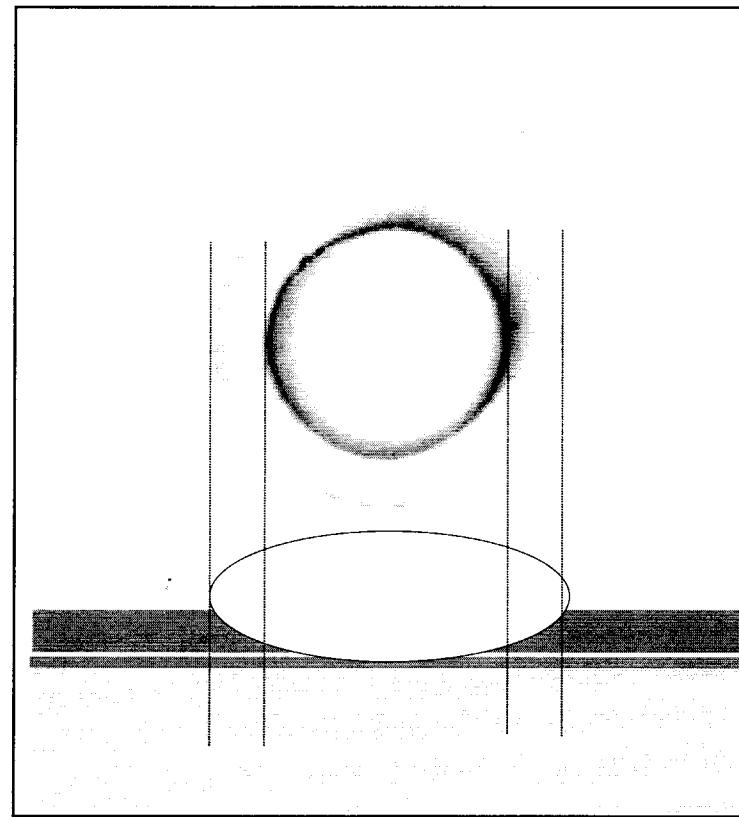
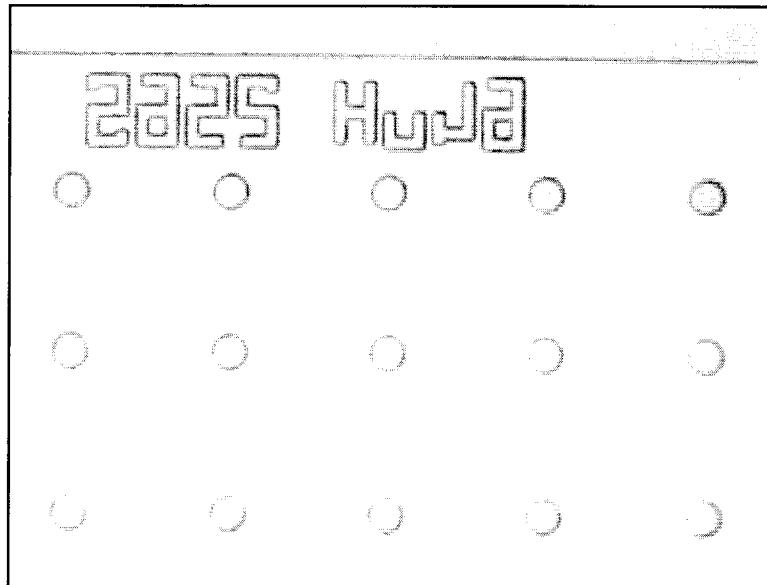
Silicon	
Chrome	
Gold	
Photoresist	



# Image of MEMS Mask



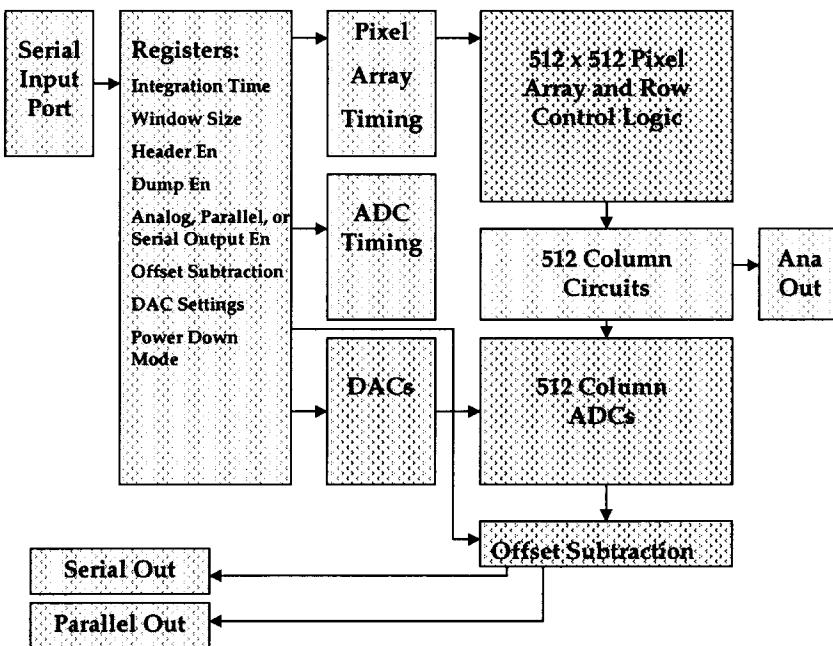
Electron Microscope Image of the MEMS Mask





# APS Image Detector

- Single camera on a chip
- A/D converter, control logic etc. included on chip
- Interfaces to PC parallel port (IEEE 1284)
- Single 5V power supply



Characteristics	Values
Technology	CMOS, 0.5µm
Outputs	Analog & Digital
Format	512 x 512
Pixel Size	12 µm x 12 µm
Responsivity	4 µV/photon
Quantum efficiency	42% (peak @ 550 nm)
Dark Current	300 pA/cm <sup>2</sup>
Noise	40 e <sup>-</sup>
Full Well	325.000 e <sup>-</sup>
Power	10 mW @ 30 FPS



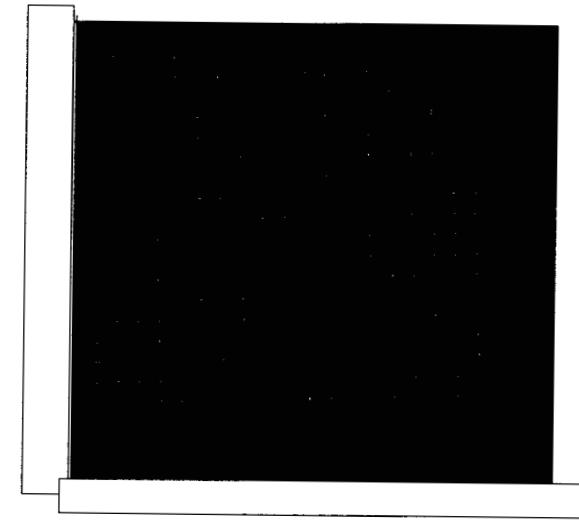
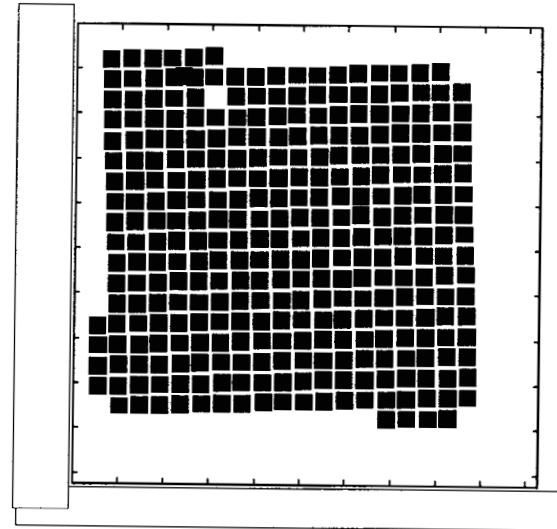
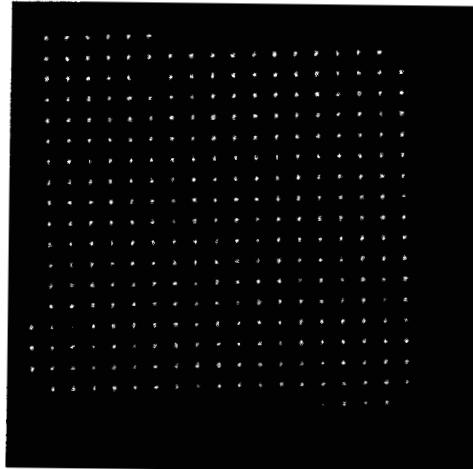
# Conventional Image Processing

Search image for pixels  
brighter than threshold

Place square box on spot

Subtract Background

Calculate centroid ( $x_{cm}, y_{cm}$ )



$$x_{cm} = \sum_{i=ROIstart,i}^{ROIend,i} \sum_{j=ROIstart,j}^{ROIend,j} \frac{i \cdot image(i, j)}{DN}$$

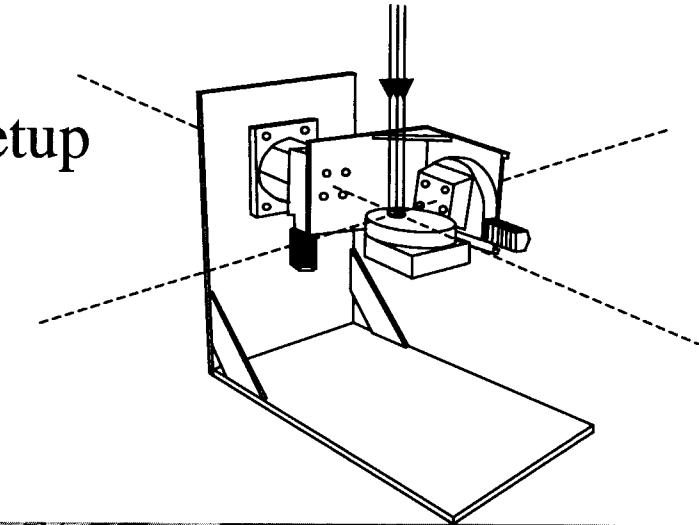
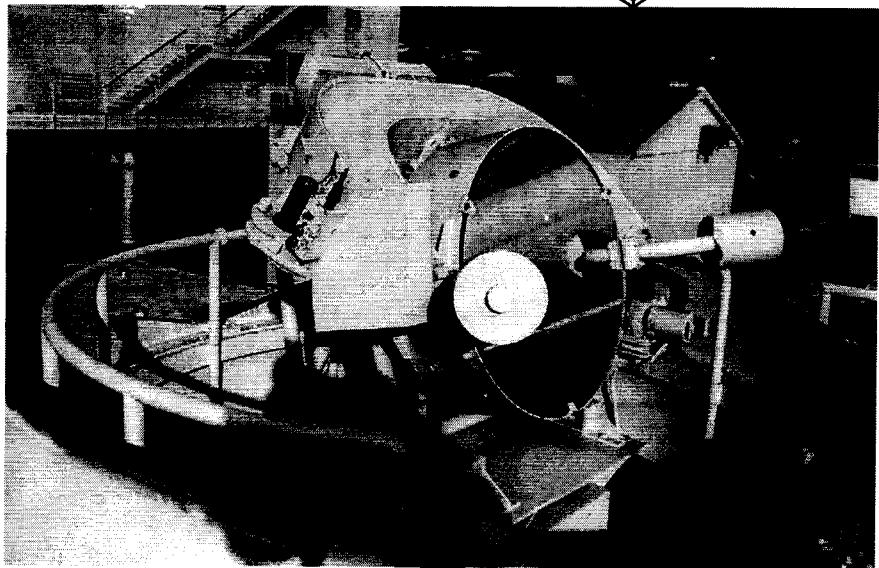
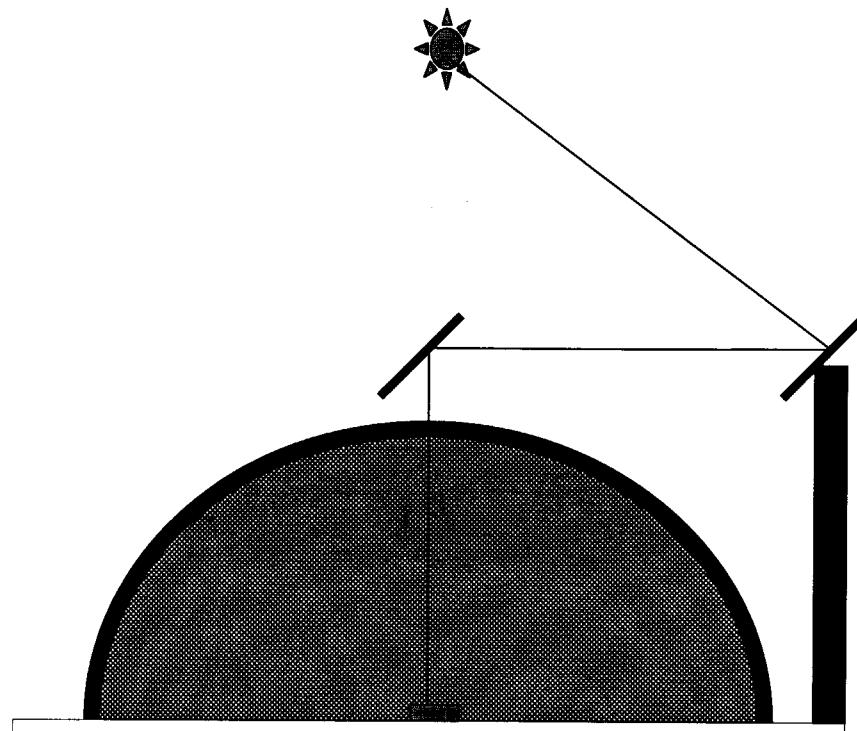
$$y_{cm} = \sum_{i=ROIstart,i}^{ROIend,i} \sum_{j=ROIstart,j}^{ROIend,j} \frac{j \cdot image(i, j)}{DN}$$

Where:  $DN = \sum_{i=ROIstart,i}^{ROIend,i} \sum_{j=ROIstart,j}^{ROIend,j} image(i, j)$



# Testing of Sun Sensor

- Sun sensor taken to Heliostat facility
- Sun sensor placed in 2 axis gimbal setup
- Images acquired in many known orientations



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# Camera model/Calibration

Rotation matrix for rotation  $\alpha$  around the x axis:

$$A_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{pmatrix}$$

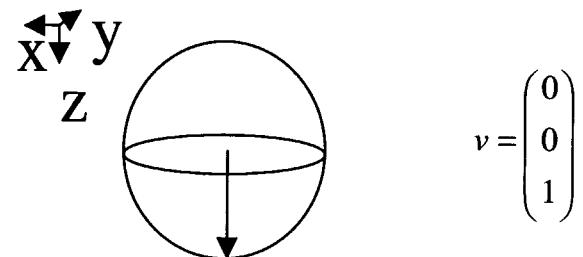
Rotation matrix for rotation  $\beta$  around the y axis:

$$A_y = \begin{pmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{pmatrix}$$

Rotation matrix for rotation  $\beta$  around y axis and then  $\alpha$  around x axis:

$$A_{xy} = A_x \cdot A_y = \begin{pmatrix} \cos \beta & 0 & \sin \beta \\ \sin \alpha \sin \beta & \cos \alpha & -\sin \alpha \cos \beta \\ -\cos \alpha \sin \beta & \sin \alpha & \cos \alpha \cos \beta \end{pmatrix}$$

The sun vector-representing zero angles:



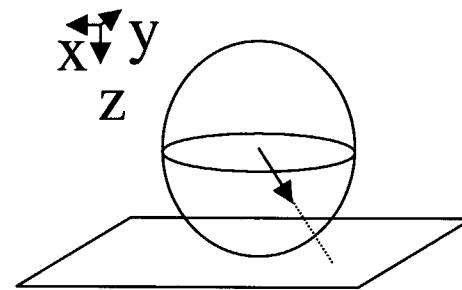


# Camera model/Calibration (Cont'd)

Unit sun vector:

$$v = A_{xy} \cdot v = \begin{pmatrix} \cos \beta & 0 & \sin \beta \\ \sin \alpha \sin \beta & \cos \alpha & -\sin \alpha \cos \beta \\ -\cos \alpha \sin \beta & \sin \alpha & \cos \alpha \cos \beta \end{pmatrix} \cdot \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \sin \beta \\ -\sin \alpha \cos \beta \\ \cos \alpha \cos \beta \end{pmatrix}$$

It is assumed that the distance from the aperture to the focal plane is 1



The z coordinate of the focal plane is 1

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \frac{x}{z} \\ \frac{y}{z} \\ 1 \end{pmatrix} = \begin{pmatrix} \frac{\sin \beta}{\cos \alpha \cos \beta} \\ \frac{-\sin \alpha \cos \beta}{\cos \alpha \cos \beta} \\ 1 \end{pmatrix} = \begin{pmatrix} \tan \beta \\ -\tan \alpha \\ 1 \end{pmatrix}$$



# Camera model/Calibration (Cont'd)

Camera parameter	Sketch	Equation
Focal length F		$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} F \cdot \frac{\tan \beta}{\cos \alpha} \\ -F \cdot \tan \alpha \end{pmatrix}$
Offset Angle		$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} F \cdot \frac{\tan(\beta - \beta_0)}{\cos(\alpha - \alpha_0)} \\ -F \cdot \tan(\alpha - \alpha_0) \end{pmatrix}$
Roll Rotation		$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} F \cdot \frac{\tan(\beta - \beta_0)}{\cos(\alpha - \alpha_0)} \cdot \cos \phi - F \cdot \tan(\alpha - \alpha_0) \cdot \sin \phi \\ -F \cdot \frac{\tan(\beta - \beta_0)}{\cos(\alpha - \alpha_0)} \cdot \sin \phi - F \cdot \tan(\alpha - \alpha_0) \cdot \cos \phi \end{pmatrix}$
x & y Offset		$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} F \cdot \frac{\tan(\beta - \beta_0)}{\cos(\alpha - \alpha_0)} \cdot \cos \phi - F \cdot \tan(\alpha - \alpha_0) \cdot \sin \phi - x_0 \\ -F \cdot \frac{\tan(\beta - \beta_0)}{\cos(\alpha - \alpha_0)} \cdot \sin \phi - F \cdot \tan(\alpha - \alpha_0) \cdot \cos \phi - y_0 \end{pmatrix}$



# Camera model/Calibration (Cont'd)

Measured image centroids and known angles

$$\bar{\alpha} = \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_{336} \end{pmatrix} \quad \bar{\beta} = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_{336} \end{pmatrix} \quad \bar{x}_m = \begin{pmatrix} x_{m,1} \\ x_{m,2} \\ \vdots \\ x_{m,336} \end{pmatrix} \quad \bar{y}_m = \begin{pmatrix} y_{m,1} \\ y_{m,2} \\ \vdots \\ y_{m,336} \end{pmatrix}$$

Find the six camera parameters that minimizes the equation below

$$\sum_{i=1}^{336} \left( F \frac{\tan(\beta_i - \beta_0)}{\cos(\alpha_i - \alpha_0)} \cos \phi - F \tan(\alpha_i - \alpha_0) \sin \phi - x_0 - x_{m,i} \right)^2 + \\ \sum_{i=1}^{336} \left( -F \frac{\tan(\beta_i - \beta_0)}{\cos(\alpha_i - \alpha_0)} \sin \phi - F \tan(\alpha_i - \alpha_0) \cos \phi - y_0 - y_{m,i} \right)^2$$

Camera parameters:

$$x_0 = 352.08 \quad F = 907.7\mu \quad \alpha_0 = -1.25^\circ \\ y_0 = 369.54 \quad \phi = 0.808^\circ \quad \beta_0 = 1.26^\circ$$

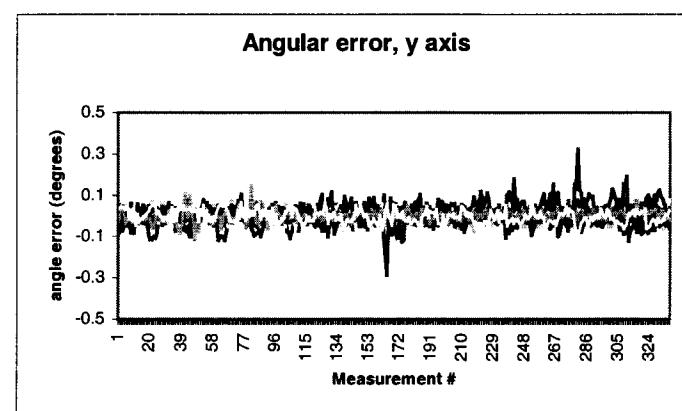
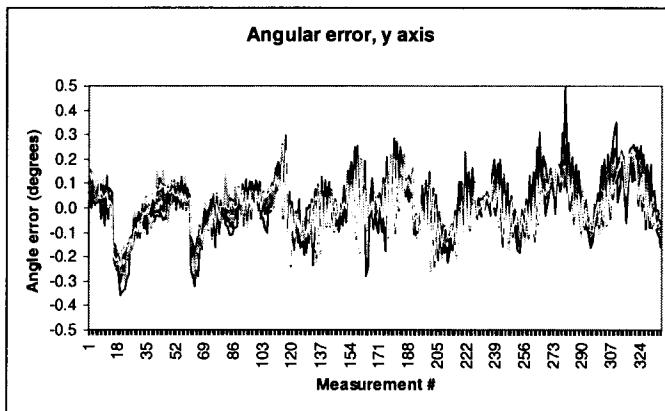
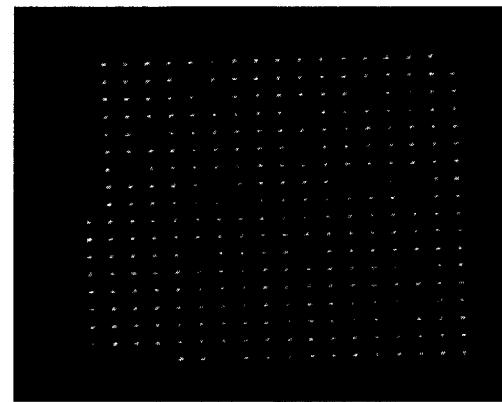
Calibration Residual

0.17 pixel



# Multiple Aperture Investigation

- 10 Apertures investigated
- Single aperture accuracy  $0.1^\circ$
- Large Systematical errors
- Systematical errors removed indicates accuracy potential of  $0.04^\circ$





# Conclusion

- Sun sensor based on MEMS technology has been developed
- Sunsensor is pinhole camera with multiple pinholes. Camera is sensitive in 1.0-1.1 micron region
- MEMS mask consist of 500 micron thick silicon wafer coated with 570 Angstrom chrome and 2000 Angstrom gold
- Image detector consists of APS camera on a chip
- Accuracy potential of 0.04 degrees
- Sun sensor is an order of magnitude miniaturized compared to state of the art sun sensors